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The Most Metal-Poor Quadruple System of Subdwarfs G89-14

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Abstract. The system of subdwarfs G89-14 is one of the most metal-poor multiple stars with an atmospheric metal abundance [m/H] = −1.9. Speckle interferometry at the 6-m BTA telescope has revealed that G89-14 consists of four components. Measurements of the magnitude difference between the components and published data have allowed their masses to be estimated: $M_A \approx 0.67\ M_\odot$, $M_B \approx 0.24\ M_\odot$, $M_C \approx 0.33\ M_\odot$, and $M_D \approx 0.22\ M_\odot$. The ratio of the orbital periods of the subsystems has been obtained, 0.52 yr : 3 000 yr : 650 000 yr (1:5769:1250000), indicative of a high degree of hierarchy of G89-14 and its internal dynamical stability. The calculated Galactic orbital elements and the low metallicity of the quadruple system suggest that it belongs to the Galactic halo.

1. INTRODUCTION

Multiple star systems (with $\geqslant$ 3 components) are currently believed to be a natural result of star formation (Kroupa et al. 2003; Delgado-Donate et al. 2003). At least 8% of the solar-type stars consist of three or more components (Tokovinin 2008). Since multiple systems are characterized by additional parameters compared to single and double stars (the angles between the orbital planes of various subsystems, eccentricity ratios, etc.), their study allows more stringent constraints to be imposed on the star formation process. Star formation models must predict the properties of such objects, while the theory of dynamical evolution must predict their survivability under both internal (tidal interactions) and external (the influence of the Galaxy's nonuniform gravitational field) effects.

Investigating metal-poor multiple stars ([Fe/H] < -1) is important in understanding the stability of star systems, because the stars with a low atmospheric metal abundance were generally formed at the epoch when our Galaxy was born, i.e., more than 10 Gyr ago. Studying multiple systems that have survived over such a long period allows one not only to test various criteria for dynamical stability of multiple stars but also to impose constraints on the mass distribution in the Galaxy.

In 2006 and 2007, we conducted a speckle interferometric survey of 223 nearby F, G, and early-K subdwarfs ($\leq$ 250 pc) with low metallicities ([Fe/H] < -1) and large proper motions ($\mu \geq 0.26''$/yr) at the 6-m BTA telescope of the Special Astrophysical Observatory, Russian Academy of Sciences (Rastegaev et al. 2007, 2008; Rastegaev 2009). The goal of the survey of Population II stars, which was carried out with the diffraction-limited angular resolution of the 6-m telescope ($0.023''$ at 550 nm), was to expand the database of double and multiple old stars and to determine the orbital parameters and properties of their components. One of the results of this survey was the discovery of the quadruple system of subdwarfs G89-14 (HIP 35756).

In this paper, we present the fundamental parameters of this system obtained from our observations and published data.

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2. OBSERVATIONS

The speckle observations of G89-14 were performed at the 6-m BTA telescope of the Special Astrophysical Observatory, Russian Academy of Sciences, in December 2006 and March 2007 (Rastegaev et al. 2007, 2008). In the observations, we used a system (Maksimov et al. 2009) based on a 512×512-pixel EMCCD (Electron Multiplying CCD) with a high quantum effciency and linearity, which allowed objects with a magnitude difference between the components $\Delta m \lesssim 5^m$ to be discovered with the diffraction-limited resolution of the 6-m telescope. The size of the detector field, $4''$ made it possible to detect the secondary components at angular distances as large as $3''$ from the primary star.

In December, under good weather conditions (seeing $< 1''$), we accumulated 500 20-ms exposures for G89-14 through a 800/100 nm filter (the first and second numbers give the central wavelength of the filter passband and the passband FWHM, respectively). In March, the weather conditions were not optimal for speckle observations ($\approx 3''$). We obtained 2000 speckle images with 20-ms exposures through each of the two filters, 550/20 and 800/100 nm.

Table 1. Results of speckle measurements for G89-14

ρ ($''$)	σ_ρ	Θ ($^\circ$)	σ_Θ	Δm	$\sigma_{\Delta m}$	$\lambda/\Delta\lambda$, nm	Epoch
0.979	0.009	0.8	0.4	4.1	0.4	800/100	2006.94455
0.982	0.005	0.8	0.4	4.3	0.1	800/100	2007.24040
Unresolved						550/20	2007.24040

We calibrated the measurements based on the so-called "standard" pairs — binary systems with well known separations between the components and position angles. The technique for determining the relative positions and magnitude differences of the components of the objects under study from speckle interferograms averaged over a series of power spectra was described by Balega et al. (2002). The accuracy achieved with this technique is 0.02^m for the magnitude difference, 1 mas for the angular separation, and 0.1° for the position angle.

The results of our measurements for the speckle interferometric subsystem of G89-14 are presented in Table 1. The March observations through the 550/20 filter did not reveal the speckle interferometric component at a distance of $0.98''$ from the known spectroscopic pair (see below), because its magnitude in this spectral range was fainter than that of the SB1 system by more than 5^m. At the same time, the observations through the 800/100 filter in March 2007 confirmed, within the error limits, the results of our interferometric observations in December 2006.

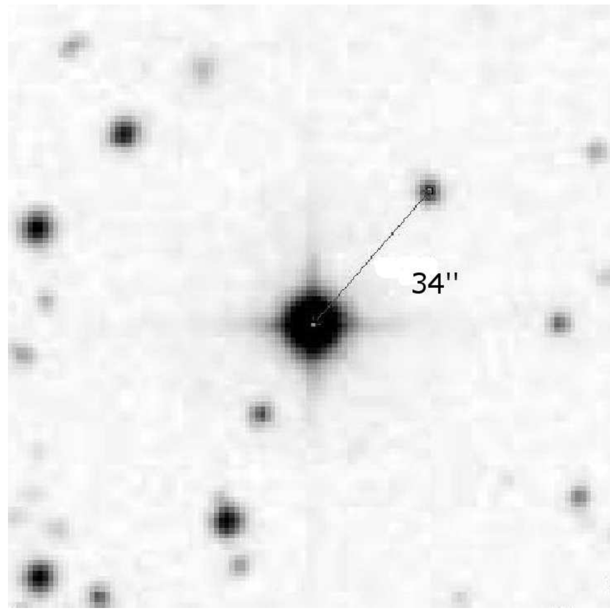

Fig. 1. Image of G89-14 from the DSS2 red survey: the triple subsystem consisting of the spectroscopic pair and the speckle interferometric component is at the center; the component with a common proper motion is located $34''$ to the northwest. In the figure taken from the Aladin database, the north is at the top and the east is to the left.

3. G89-14: A SYSTEM OF FOUR SUBDWARFS

Initially, G89-14 (TYC 763-801-1; HIP 35756; WDS 07224+0854; NLTT 17770) with coordinates $07^h22^m31\overset{s}{.}5$ $+08^\circ49'13.0''$ (J2000.0) was known as an SB1-type spectroscopic binary system with a period of about 190 days (Latham et al. 1988, 2002). Subsequently, Allen et al. (2000) found a companion to this pair with a common proper motion located at an angular distance of $34''$. Unfortunately, these authors did not give the position angle of this companion. In the Aladin database, there is only one star at a distance of $34''$ that we took as the component with a common proper motion (Fig. 1). Allen et al. (2000) refuted the physical connection of G89-14 with G89-13 (HIP 35750), because, having a common proper motion, the parallax and radial velocity of G89-13 differed significantly from those of G89-14. In 2006, using the BTA telescope, we discovered a speckle interferometric component at an angular distance of $\approx 1''$ from the spectroscopic binary (Rastegaev et al. 2007, 2008). According to the Hippacros data, the heliocentric distance of G89-14 is ≈ 170 pc (ESA 1997). The distance determined by Carney et al. (1994) from the photometric parallax is 94 pc and is most likely an underestimate, because it disregards the presence of additional components. At a distance of 170 pc from the Sun, the probability that the speckle interferometric companion at an angular distance of $0.98''$ and with a magnitude difference of about 4^m is an optical projection is insignificant. Hence, we concluded that the discovered companion and the system G89-14 are physically connected. Their gravitational connection is also confirmed by the repeated interferometric observations in March 2007. If the component were an optical projection, then, given the large proper motion of G89-14, $\mu \approx 0.3''$/yr (Carney et al. 1994; ESA 1997), the relative position of the component would change by $\approx 0.1''$ in the time between our observations (from December to March), which exceeds the errors of our speckle measurements. Thus, four gravitationally bound components of the system are known at present (Fig. 2). The metallicity of G89-14 is [m/H] $= -1.9$ (Carney et al. 1994). Analysis of the literature has shown that none of the quadruple stars known to date has such a low metal abundance.

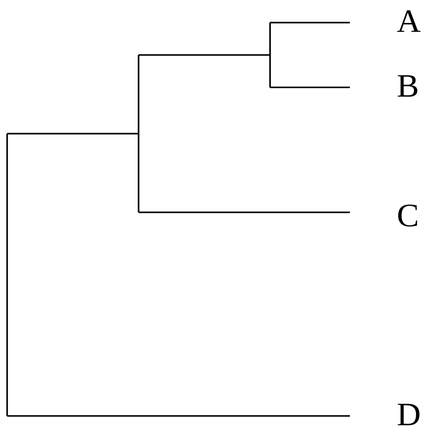

Fig. 2. Schematic representation of the hierarchy levels for G89-14: A–B is the spectroscopic subsystem, AB–C is the speckle interferometric subsystem, and ABC–D is the subsystem with a common proper motion.

4. ESTIMATES OF THE COMPONENT MASSES

Accurate stellar masses can be determined only in binary and multiple systems by constructing their orbits. In the remaining cases, only approximate estimates based on various theoretical and empirical relations (e.g., the mass-luminosity relation) are possible. All orbital parameters are known for none of the subsystems of G89-14. A spectroscopic orbit was obtained for the shortest-period subsystem with a period of 190.49 ± 0.29 days (Latham et al. 2002). However, in this case, the inclination i of the orbital plane to the plane of the sky remains unknown.

Using evolutionary tracks, spectroscopic (Carney et al. 1994) and photometric (Allen et al. 2000; Monet et al. 2003) data, and our speckle observations, we estimated the masses of the components in the quadruple system under consideration.

Based on the tracks from Vandenberg and Bell (1985) and the spectroscopically measured metallicity and temperature of the primary component (5750 K) of the spectroscopic subsystem of G89-14, Carney et al. (1994) estimated its mass to be 0.67 $M_\odot$. The mass function that they obtained from spectroscopic observations,

$$\frac{M_B^3 \sin^3 i}{(M_A + M_B)^2} = 0.0173, \tag{1}$$

allows the mass of the secondary spectroscopic component to be determined to within a factor of $\sin^3 i$. Substituting $M_A = 0.67\ M_\odot$ into Eq. (1) and setting $\sin^3 i = 1$, we obtain the lower mass limit $M_B \geq 0.24\ M_\odot$.

The mass of the speckle interferometric companion was estimated from the total magnitude of the triple subsystem (the SB1 pair and the interferometric component), 10.0^m in the I band (Monet et al. 2003), and from the magnitude difference between the spectroscopic binary and the companion we discovered (Table 1). For our calculations, we took $\Delta m = 4.2$ in the 800/100 filter, which roughly corresponds to the I band. The apparent magnitude of the speckle interferometric component was 14.22^m. Based on the absolute magnitude of the companion ($M_I = 8.07^m$) and using the evolutionary tracks for [Fe/H] $= -2.0$ from Baraffe et al. (1997), we estimated the mass of the interferometric component to be $\approx 0.33\ M_\odot$.

Allen et al. (2000) gave the absolute magnitude of the most distant component $M_V = 10.4^m$, which, according to the evolutionary tracks from Baraffe et al. (1997), corresponds to a mass of $0.22 M_\odot$ for the metallicity [Fe/H] $= -2.0$. Judging by the mass function from Chabrier (2003) derived for the Galactic halo stars, this mass is a mean for the halo field stars. Note that the distance to the star used by Allen et al. (2000) is slightly larger, 180 pc instead of 170 pc that we adopted. We did not apply a correction to the mass estimate for this component due to the difference between the assumed heliocentric distances.

Thus, denoting the primary component of the spectroscopic pair, its closest companion, the speckle interferometric component, and the most distant component with a common proper motion by A, B, C, and D, respectively (Fig. 2), we have $M_A \approx 0.67\ M_\odot$, $M_B \approx 0.24\ M_\odot$, $M_C \approx 0.33\ M_\odot$, $M_D \approx 0.22\ M_\odot$.

5. ORBITAL PERIODS OF THE SUBSYSTEMS AND DYNAMICAL STABILITY

Using the above mass estimates and Kepler's generalized third law, we calculated the unknown periods of two subsystems of G89-14. The semimajor axis appearing in Kepler's law was determined for each subsystem from an empirical relation between the projected component separation and the orbital semimajor axis. Given the parallax of the system π and the projected separation between the components ρ, the expected semimajor axis can be calculated from the formula (Allen et al. 2000)

$$\langle a \rangle = 10^{\log \frac{\rho}{\pi} + 0.146}, \tag{2}$$

where $\langle a \rangle$ is in astronomical units, ρ and π are in arcseconds.

Our calculations show that the speckle interferometric component and the SB1 pair make one revolution around the common center of mass approximately in 3000 yr (P_{AB-C}), while the revolution period of the most distant component and the triple subsystem is about 650000 yr (P_{ABC-D}). For the outer subsystem, we took the expected semimajor axis $\langle a \rangle = 8565$ AU from Allen et al. (2000). The ratio of the subsystem periods, 1 : 5769 : 1250000, is indicative of a high degree of hierarchy of G89-14 and, hence, its internal dynamical stability. Nevertheless, the outer subsystem has a low binding energy and is subjected to the destructive effect from giant molecular clouds and the stellar component of our Galaxy (Weinberg et al. 1987).

Table 2. Initial conditions for constructing the Galactic orbit of G89-14

v_{rad}, km/s	μ, $''$/yr	D, pc	$\widetilde{\omega}$, kpc	z, kpc	Φ, km/s	W, km/s	h, km·kpc/s
−36.9	0.31	170	8.15	0.03	−165	13	194

6. GALACTIC ORBIT

To ascertain which subsystem of our Galaxy (halo, thick or thin disk) G89-14 belongs to, apart from the atmospheric metal abundance, it is also necessary to know the pattern of motion of the object in the Galactic gravitational field. The most complete description of the star's dynamical properties is the construction of its Galactic orbit.

To construct the Galactic orbit, we must find a solution to the equations of motion in the gravitational potential of the Galaxy. For an axisymmetric potential, the specific angular momentum is a conserved quantity and the motion can be described in a moving meridional plane. In cylindrical coordinates, the motion of the star in the meridional plane is described by a system of second-order differential equations:

$$\frac{d^2\widetilde{\omega}}{dt^2} = -\frac{\partial\phi}{\partial\widetilde{\omega}} + \frac{h^2}{\widetilde{\omega}^3}, \tag{3}$$

$$\frac{d^2z}{dt^2} = -\frac{\partial\phi}{\partial z}. \tag{4}$$

At the same time, the motion of the meridional plane itself is specified by the equation

$$\frac{d\theta}{dt} = \frac{h}{\widetilde{\omega}^2}, \tag{5}$$

where ϕ is the gravitational potential of our Galaxy, $h = \Theta \cdot \widetilde{\omega}$ is the specific angular momentum of the body, $\widetilde{\omega} = \sqrt{X^2+Y^2}$, $\theta = \mathrm{arctg}(Y/X)$ and $z = Z$ are the cylindrical Galactic coordinates, and Θ is the projection of the space velocity vector corresponding to coordinate θ; X, Y and Z are the coordinates of the object in the rectangular coordinate system with the origin at the Galactic center and with the XY plane coincident with the Galactic plane. The second term on the right-hand side of Eq. (3) is the Coriolis acceleration acting on the body in the rotating frame of reference.

The initial conditions in solving the equations of motion (3)–(5) are the position and velocity of the star in the Galaxy. To specify the initial conditions, we must know six observable quantities: the object's coordinates (l and b), proper motions in α (μ_α, $''$/yr) and δ (μ_δ, $''$/yr), parallax (π, $''$), and radial velocity (v_{rad}, km/s). Table 2 presents the input data for integrating the Galactic orbit of G89-14. The projection of the space velocity vector onto $\widetilde{\omega}$ is denoted by Φ. In our calculations, we assumed the distance from the Galactic center to the Sun to be $\widetilde{\omega}_\odot = 8$ kpc and the solar motion relative to the Local Standard of Rest to be $(U_\odot, V_\odot, W_\odot) = (-10.0,\ 5.0,\ 7.0$ km/s) (Dehnen and Binney 1998). Using formulas from Johnson and Soderblom (1987), we passed from the observable quantities (ESA 1997; Latham et al. 2002) to the projections of the space velocities of G89-14 in the rectangular coordinate system, $(U, V, W) = (-165,\ -195,\ 13$ km/s).

To calculate the parameters of the body's Galactic orbit, it will suffice to solve two equations of motion, (3) and (4), numerically. For the solution, we used the seventh-order Runge–Kutta–Nyström method with a variable step (see, e.g., Fehlberg 1972). The parameters of the derived Galactic orbit of G89-14 are presented in Table 3. As the gravitational potential of our Galaxy, we chose a three-component model described by Allen and Santillan (1991). Figure 3 shows the orbit of G89-14. Over 10^{10} yr, the system has crossed the Galactic plane ~ 100 times. G89-14 may have had a larger number of components that were lost through the tidal effect from the Galaxy, because part of the time the system moved in the Galactic plane, where this effect is maximal. We see from the figure that during its multiple revolutions, the star has closely approached the Galactic center ($\widetilde{\omega}_{min} = 0.3$ kpc). The orbit is clearly chaotic and has a high eccentricity, which was determined from the formula

$$e = \frac{R_{apo} - R_{peri}}{R_{apo} + R_{peri}},$$

where $R = \sqrt{\widetilde{\omega}^2 + z^2}$; R_{apo} and R_{peri} are the maximum and minimum distance of the star from the Galactic center. The orbital parameters, along with the low metallicity, allow us to confidently classify the object under study as belonging to the halo population.

Carney et al. (1994) also obtained the parameters of the Galactic orbit for G89-14, suggesting that the star most likely belongs to the thin or thick disk. Given the low atmospheric metal abundance in the star, its belonging to the Galactic disk is less plausible. The main error in their calculations was the underestimated heliocentric distance (94 pc) determined by Carney et al. from the photometric parallax.

7. CONCLUSIONS

Our speckle observations at the 6-m BTA telescope revealed that G89-14 consists of four subdwarfs. A review of the literature showed that G89-14 with [m/H] = −1.9 is the most metal-poor quadruple system known to date. This made it an interesting object for a more detailed study.

Based on evolutionary tracks (Baraffe et al., 1997), available spectroscopic (Carney et al. 1994) and photo-

Table 3. Parameters of the Galactic orbit for G89-14

$\widetilde{\omega}_{min}$	$\widetilde{\omega}_{max}$	z_{min}	z_{max}	e
0.3 kpc	10.1 kpc	−6.5 kpc	6.4 kpc	0.93

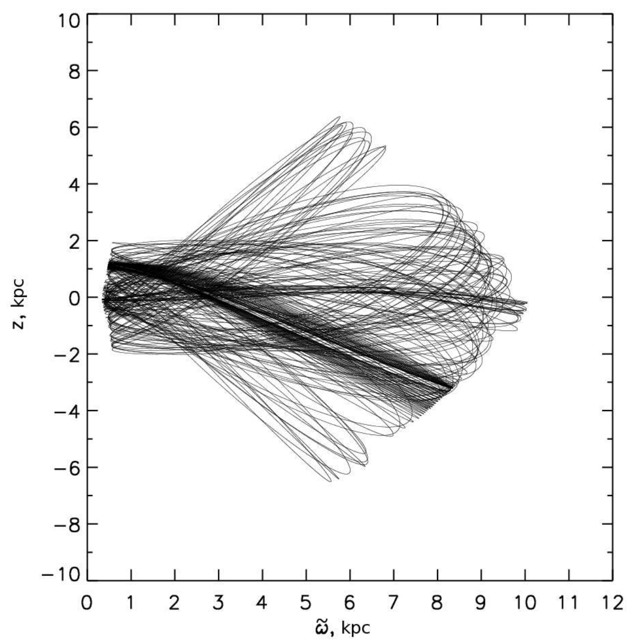

Fig. 3. Galactic orbit of G89-14.

metric (Allen et al. 2000; Monet et al. 2003) data, and our speckle interferometry, we estimated the masses of the components of G89-14: $M_A \approx 0.67\ M_\odot$, $M_B \approx 0.24\ M_\odot$, $M_C \approx 0.33\ M_\odot$, $M_D \approx 0.22\ M_\odot$. The ratio of the orbital periods of the subsystems $P_{AB} : P_{AB-C} : P_{ABC-D} =$ 0.52 yr : 3000 yr : 650000 yr (1:5769:1,250,000) is indicative of a high degree of hierarchy of G89-14 and, consequently, its high internal dynamical stability. Using the three-component model of the gravitational potential by Allen and Santillan (1991), we constructed the Galactic orbit of the quadruple star under consideration (Fig. 3). Analysis of the Galactic orbital elements and the low metallicity of the system suggest that G89-14 belongs to the Galactic halo. Further observations of G89-14 by various methods are needed to improve the orbital elements of the subsystems and the fundamental parameters of the system's components.

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